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Subkilohertz comparison of the single-ion optical-clock $^2S_{1/2}$-$^2D_{5/2}$ transition in two $^{88}Sr^+$ traps

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A simultaneous observation of the optical-clock $^2S_{1/2}$-$^2D_{5/2}$ transition at 674 nm, in two separately trapped single $^{88}Sr^+$ ions, is reported. Two nominally identical miniature rf Paul traps were used together with a 674-nm sideband-injection-locked extended-cavity diode laser. This ''slave'' laser was optically phase locked about 650 MHz away from a ''master'' diode laser, which was itself locked to a high-finesse, ultra-low-expansion (ULE) cavity. The ULE cavity was temperature-stabilized and suspended in an evacuated enclosure, and provided an ''optical flywheel'' reference standard with a relative drift rate of better than 1 part in 10^{11} per hour. The difference between center frequencies of the single $^{88}Sr^+$-ion 674-nm (445-THz) transition multiplet in two traps was 120(90) Hz (one standard uncertainty). Thus the two trap center frequencies agree to 3 parts in 10^{13}. [S1050-2947(99)50405-8]

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INTRODUCTION

Future optical frequency standards may be based on references in trapped ions, and transitions in a number of ion species are being investigated [1]. One possible frequency reference is the quadrupole $^2S_{1/2}$-$^2D_{5/2}$ transition in ions with an alkali-metal-like term structure. The natural width of these transitions is in the region of 1 Hz. For example, in $^{88}Sr^+$, the $^2S_{1/2}$-$^2D_{5/2}$ ''optical-clock'' transition at 674 nm has a natural width of ≈0.4 Hz. The transition frequency has been measured at both the UK National Physical Laboratory (NPL) [2] and the National Research Council of Canada (NRC) [3–5]. The $^{88}Sr^+$ 674-nm transition was recently recommended by the Comité International des Poids et Mesures as a new radiation for the realization of the meter [6] and is the first ion-trap-based optical frequency standard to be so included. The agreement between measurements of the 674-nm $^2S_{1/2}$-$^2D_{5/2}$ optical-clock transition frequency made at NPL and NRC is currently at the 100-kHz level. The NPL measurement used precision interferometric techniques relative to a 633-nm iodine stabilized laser [2], while NRC used both a heterodyne link to 633 nm [3,4,6] and a preliminary chain arrangement direct to a 9.2-GHz Cs primary standard. Improved measurements are planned at both laboratories [4,7].

While it is important to determine the absolute frequency of the 674-nm transition in $^{88}Sr^+$, it is also necessary to investigate its stability and reproducibility. At NPL, a program is underway to study these parameters by comparing the 674-nm transition in two separately trapped $^{88}Sr^+$ ions. This paper reports the subkilohertz comparison of the $^{88}Sr^+$ 674-nm ''optical-clock'' transition, simultaneously observed in single ions in two nominally identical traps.

A partial term scheme of $^{88}Sr^+$, showing the Zeeman structure, is given in Fig. 1. The first-order magnetic-field dependence results in the 674-nm $^2S_{1/2}$-$^2D_{5/2}$ transition splitting into ten Zeeman components. The relative intensities of the components depend on the relative orientation of the polarization of the 674-nm radiation, the direction of the

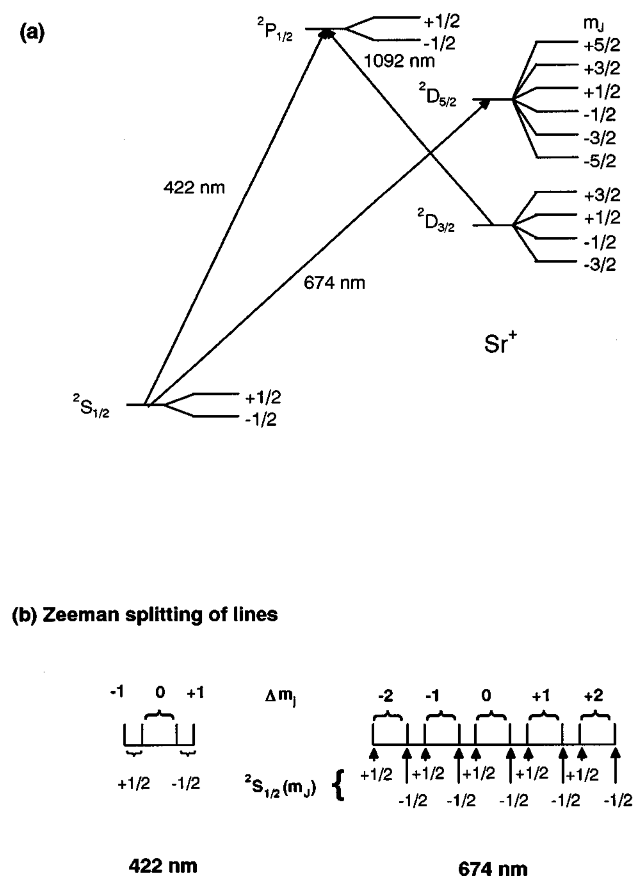

FIG. 1. A partial $^{88}Sr^+$ term scheme, showing the Zeeman splitting of all of the levels involved in the cooling and interrogation of the ion. The lower half of the figure shows the ten Zeeman components expected for the 674-nm transition and their assignments.

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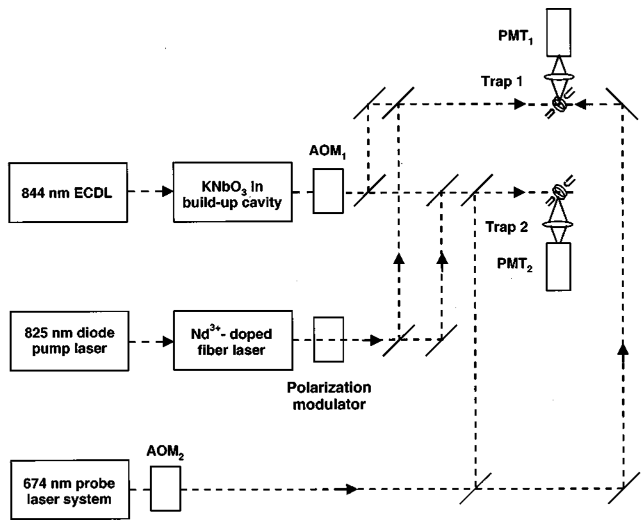

FIG. 2. Overall schematic of the probe and cooling laser system. The acousto-optic modulators (AOM_1 and AOM_2) switch the cooling and probe lasers off for both traps. The fiber laser output is also polarization modulated and the probe laser system is shown in detail in Fig. 3.

residual magnetic field, and the direction of propagation of the 674-nm radiation, due to the electric quadrupole transition selection rules. For example, with a magnetic field parallel to the direction of polarization of the linearly polarized 674-nm radiation, only the $\Delta m_J = \pm 1$ components are observed, whereas if this field were orthogonal to both the 674-nm laser polarization and direction of propagation, then only the $\Delta m_J = \pm 2$ lines would be observed [8].

TRAP AND LASER SYSTEM

Figure 2 shows a schematic diagram of the two-trap experiment and associated lasers. The miniature rf Paul traps are identical to one described elsewhere [2,9], and have a radius of ≈0.5 mm. The two traps had slightly different rf drive frequencies of 12.4 MHz and 14.2 MHz. Shields were incorporated in the oven design to prevent the strontium atomic beam from coating the Brewster-angled entrance window to the trap. The ions, one in each trap, were cooled using the $^2S_{1/2}$-$^2P_{1/2}$ transition at 422 nm, and the same frequency-doubled laser diode system was used for both traps [9–11]. A Nd^{3+}-doped fiber laser was also required, and this was tuned to the $^2P_{1/2}$-$^2D_{3/2}$ transition, in order to prevent the loss of the ions from the cooling cycle by decay into the $^2D_{3/2}$ state.

For this two-$^{88}Sr^+$-trap work, a different probe laser arrangement was used and is shown in Fig. 3. The 674-nm source was a sideband-injection-locked ''slave'' extended-cavity diode laser [12,13]. Sidebands were imposed on the slave laser and one of these was optically locked to a ''master'' laser that was injected into the slave via a half-wave plate that was used to vary the power by adjusting the relative orientation of the polarizations of the two lasers. The master laser was another 674-nm diode laser, prestabilized using resonant optical feedback, and locked to a high-finesse, temperature-stabilized nontunable ultra-low-expansion (ULE) cavity, suspended in an evacuated enclosure [2]. The slave laser was offset ≈650 MHz away from a master laser. This offset was determined by the frequency of the sidebands imposed on the slave laser and was chosen to bridge the frequency interval between the Sr^+ $^2S_{1/2}$-$^2D_{5/2}$ 674-nm transition and the nearest mode of the ULE cavity. The modulation was provided by an oscillator controlled by a personal computer (PC) through an Institute of Electrical and Electronic Engineers 488.2 interface. The long-term drift of the master laser, which was determined by the drift of the ULE cavity, was ≈4 kHz/day, but larger cyclic drifts of up to 3 kHz/h were observed. This was probably due to daily room-temperature changes affecting the ULE cavity temperature. During the time taken for each scan, typically 10 min, the laser drifted by ≈500 Hz. However, over this short time scale this drift was predominantly linear and, since the same laser was being used in both traps, the effect on the observed

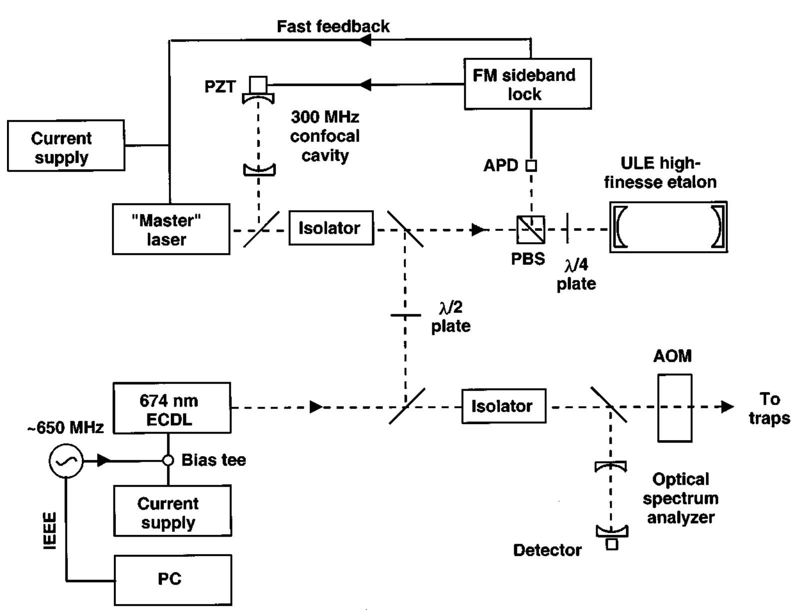

FIG. 3. Detailed arrangement of the 674-nm probe laser system. The master laser has been described previously [2], although the sideband injection locked system has only recently been implemented [12].

transition center frequency difference was negligible. The master laser linewidth is $\approx$1 kHz, as determined from the width of the observed 674-nm Zeeman components [9].

The procedure for interrogation of the $^{88}Sr^{+}$ 674-nm transition in two traps is a modification of the previously published routine [10] for one trap. The fluorescence rate at 422 nm from both traps is recorded simultaneously using a PC plug-in card, which has a number of countertimers. These may be set up so that they are gated simultaneously and store the count at the end of each gate time, which is typically set to 20 ms. The stored counts are read by the PC some time before the start of the next cycle. The cooling and probe lasers are alternately switched using acousto-optic modulators (Fig. 2). An interrogation cycle begins with the two single $^{88}Sr^{+}$ ions fluorescing, one in each trap. The PC then switches the cooling laser off in both traps, and a pulse of 674-nm radiation of a few millisecond duration follows, before the cooling light is restored. If either ion stops fluorescing, then a quantum jump event is recorded for that trap and the PC waits until fluorescence is restored in both traps before repeating the cycle. Typically 40 interrogations are made at one particular probe laser frequency before the frequency is stepped via the IEEE interface.

The two traps are housed inside μ-metal shields to reduce the effect of the ambient magnetic fields. In addition, three pairs of coils are mounted inside the μ-metal shield and the currents through them adjusted to further reduce the dc magnetic field at trap center. The currents in these coils are also varied in order to provide controlled Zeeman splitting of the 674-nm transition. The μ-metal shields also reduce the effect due to ac magnetic fields at 50 Hz produced, for example, by neighboring electronics units and mains cables.

Initially the magnetic field at the center of both traps was nulled to within a few microtesla. This was achieved by varying the current in each pair of coils, minimizing the fluorescence with the fiber laser tuned to the $^2P_{1/2}$-$^2D_{3/2}$ transition at 1092 nm in a static polarization state. Cooling and interrogation of the ion were undertaken with the 1092-nm laser polarization modulated at $\approx$2 MHz, in order to prevent optical pumping into dark states of the $^2P_{1/2}$-$^2D_{3/2}$ transition [14]. Once the magnetic field was less than a few microtesla, the separation of two symmetrically placed pairs of Zeeman components was used in order to reduce the field further. A field of typically a few microtesla was then applied to separate the Zeeman components; the magnetic-field direction could be chosen to select a particular subset of components.

TRANSITION CENTER FREQUENCY COMPARISON BETWEEN THE TWO TRAPS

A series of simultaneous two-trap scans was taken on three days. Before each scan, the level of rf micromotion along the direction of the cooling beam was minimized by adjusting the trap bias voltages using the rf-photon correlation diagnostic technique [15]. Figure 4 shows one of the simultaneous two-trap scans of the 674-nm $^2S_{1/2}$-$^2D_{5/2}$ transition over a 200-kHz region, with a step resolution of 500 Hz. The magnetic-field strength and direction were different in the two traps, but the polarization of the 674-nm radiation was horizontal in both cases. The residual magnetic field at the center of the first trap was nulled to about 1 μT using the

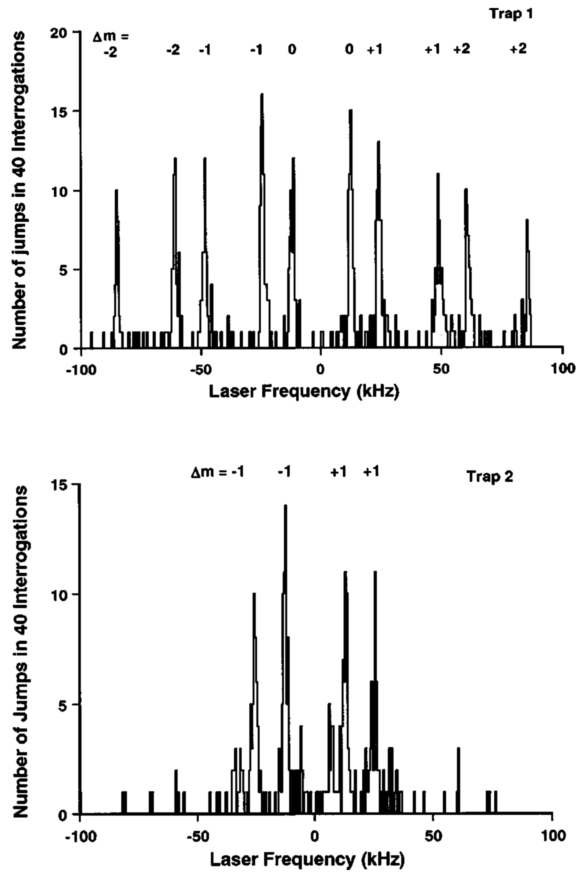

FIG. 4. A ''two-trap'' scan over the $^2S_{1/2}$-$^2D_{5/2}$ 674-nm probe transition, recorded using a frequency step size of 500 Hz. Although the individual components are significantly frequency-shifted in the presence of a magnetic field, the centers of Zeeman components (which are positioned symmetrically about the true line center) were used to estimate the transition center frequency of an individual scan to typically 200 Hz.

techniques described previously. An additional field was then applied to deliberately separate the Zeeman components, resulting in a total magnetic field of $\approx$2.2 μT, estimated from the observed Zeeman component splittings. The resultant field direction was not parallel to the direction of the laser beams and was neither parallel nor orthogonal to the 674-nm polarization. This enabled all ten Zeeman components to be observed (see Fig. 4, upper scan). The magnetic field in the second trap was estimated to be $\approx$1.1 μT, with the dominant component along the direction of the red laser. This explains why the $\Delta m_J = \pm 1$ lines were seen but $\Delta m_J = 0$ and ± 2 transitions were not observed (Fig. 4, lower scan). An additional magnetic field was not needed for the second trap since the Zeeman components were well separated.

For each of the eight two-trap scans, the line center of each Zeeman component was determined by fitting a Lorentzian curve to the feature. Fitting the data to Gaussian profiles made no significant difference to the estimated centers. The center of the $^{88}Sr^{+}$ 674-nm $^2S_{1/2}$-$^2D_{5/2}$ transition was determined by finding the midpoint between the pairs of Zeeman components lying symmetrically on either side of line center. A mean center frequency value was then estimated by averaging these results for each scan.

The average difference between the center frequencies of the single-ion $^{88}Sr^+$ $^2S_{1/2}$-$^2D_{5/2}$ transition measured in two traps for eight simultaneous pairs of 674-nm scans was 120(90) Hz. This mean was calculated from the differences determined from the individual scans. These were weighted according to the estimated transition center uncertainties from each determination. The quoted 1σ uncertainty (90 Hz) was derived from the scatter of the results obtained from the eight simultaneous scans. Thus there is no statistically significant difference between the center frequencies of the 674-nm $^{88}Sr^+$ $^2S_{1/2}$-$^2D_{5/2}$ transitions measured in the two ion traps.

While this initial study has not included any detailed study of the variation of the transition frequency with different operating parameters, the magnetic field was varied by 3.6 μT between the traps on different simultaneous scans with no observable variation in the center frequency. It is likely that the level of micromotion and secular motion in the two traps was not always exactly the same during each simultaneous scan; however, any resultant shift due the second-order Doppler shift would be well below the present level of measurement uncertainty [16]. The Zeeman components of the 674-nm $^2S_{1/2}$-$^2D_{5/2}$ transition in $^{88}Sr^+$ shift linearly with magnetic field and this may limit the ultimate accuracy of an even isotope strontium optical frequency standard. The possibility of using $^{87}Sr^+$, which has $^2S_{1/2}$-$^2D_{5/2}$ transitions that are free from the first-order Zeeman effect, has been analyzed and will be reported elsewhere [17].

CONCLUSION

A comparison of $\approx$200-kHz-wide simultaneous scans, over the single $^{88}Sr^+$-ion 674-nm transition multiplet, has been presented. To our knowledge, this is the first comparison of an optical transition interrogated in two ions confined in two separate ion traps. The average measured offset between the transition center frequencies observed in different traps was 120 Hz (3 parts in 10^{13}), with a standard uncertainty of 90 Hz. There was therefore no evidence at this level of any significant offset between the $^{88}Sr^+$ $^2S_{1/2}$-$^2D_{5/2}$ transition center frequencies observed in the two traps. The uncertainty of this comparison corresponded to the scatter in the determinations from each pair of Zeeman components in the eight scans. A narrower probe laser, together with longer interrogation times and reduced cavity drift, would improve the ability to measure these features and study systematic effects at the few-hertz level.

ACKNOWLEDGMENTS

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